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HAKOU v3: SWIMS Hurricane Inundation Fast Forecasting Tool for Hawaii

by Jane McKee Smith, Mary E. Anderson, Alexandros A. Taflanidis, Andrew B. Kennedy, Joannes J. Westerink, and Kwok Fai Cheung

PURPOSE: This Coastal and Hydraulics Engineering Technical Note (CHETN) describes HAKOU v3, a Surge and Wave Island Modeling Studies (SWIMS) fast forecasting tool that predicts hurricane inundation risk for the Hawaiian islands of Kauai and Oahu.

INTRODUCTION: U.S. Pacific Island coastal communities are extremely vulnerable to tropical cyclones. A powerful hurricane or typhoon can increase water levels and generate large waves impacting island coasts, causing coastal inundation and loss of infrastructure and life. While the complexity and accuracy in modeling coastal inundation continues to increase, most numerical models were conceived and tested primarily for U.S. mainland application. Developing methodologies to analyze accurately hurricane/typhoon waves and storm surge, and their interaction with island coasts, including coastal reefs, is the goal of SWIMS.

Pacific Land-Ocean Typhoon Experiment (PILOT) and SWIMS have worked cooperatively toward improved measurements and modeling of storm waves and inundation on island coasts. PILOT has collected coastal processes and meteorological data under hurricane and high-wind conditions in Guam, Hawaii, Saipan, and the U.S. Virgin Islands. Wave and water level data from PILOT are then used by SWIMS, which serves to evaluate and extend existing models by developing new capabilities and links between models. HAKOU v3 is a SWIMS framework that estimates hurricane flooding risk for the Hawaiian islands of Kauai and Oahu by performing dynamic and fast evaluations of waves, surge, and inundation for approaching hurricanes (Smith et al. 2011).

OVERVIEW: HAKOU employs a database of storm response to quickly forecast potential inundation risk when a storm threatens Hawaii. The database was generated from proven high-resolution wave and surge simulations covering the range of hurricanes expected to impact the islands. Hurricanes are characterized by five simple parameters: landfall location, angle of approach, minimum central pressure, forward speed, and radius of maximum winds. The database is then used to forecast quickly potential waves, surge, and inundation by employing response-surface surrogate modeling. Specifically, HAKOU calculates three different outputs: (1) maximum significant wave height, (2) maximum still water level, and (3) maximum wave runup level. HAKOU can perform either a deterministic assessment of a single hurricane track or a probabilistic assessment based on the error cone of possible tracks and forecasts. HAKOU provides deterministic predictions in seconds and probabilistic predictions in minutes. Additionally, inundation lines can be saved as shapefiles for viewing in GIS and as KML files for uploading to Google Earth.

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14. ABSTRACT
U.S. Pacific Island coastal communities are extremely vulnerable to tropical cyclones. A powerful hurricane or typhoon can increase water levels and generate large waves impacting island coasts, causing coastal inundation and loss of infrastructure and life. While the complexity and accuracy in modeling coastal inundation continues to increase, most numerical models were conceived and tested primarily for U.S. mainland application. Developing methodologies to analyze accurately hurricane/typhoon waves and storm surge, and their interaction with island coasts, including coastal reefs, is the goal of SWIMS.

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DEVELOPMENT:

Storm Selection. Since 1950, Hawaii has experienced five hurricanes: Nina (1957), Dot (1959), Iwa (1982), Estelle (1986), and Iniki (1992). Characteristic storm parameters and tracks were based on historical storms as well as guidance from the National Weather Service, because the historic storm record is relatively sparse.

Five base tracks were selected, as shown in Figure 1. These tracks represent approach angles from 120, 150, 180, 210, and 240 deg (measured clockwise from North). Three hurricane central pressures of 940, 955, and 970 mbar were used to represent hurricane intensity. The size of the storm was characterized by radii of maximum winds of 30, 45, and 60 km. Forward speeds of 7.5, 15, and 22.5 kts were considered, and 15 landfall locations were selected along the south shorelines of Oahu and Kauai and between the islands. Not all radii, speeds and intensities were modeled for all tracks; the grid of storms was chosen to balance computational effort but still extend over the entire range of hurricanes that can have significant impact to the islands.

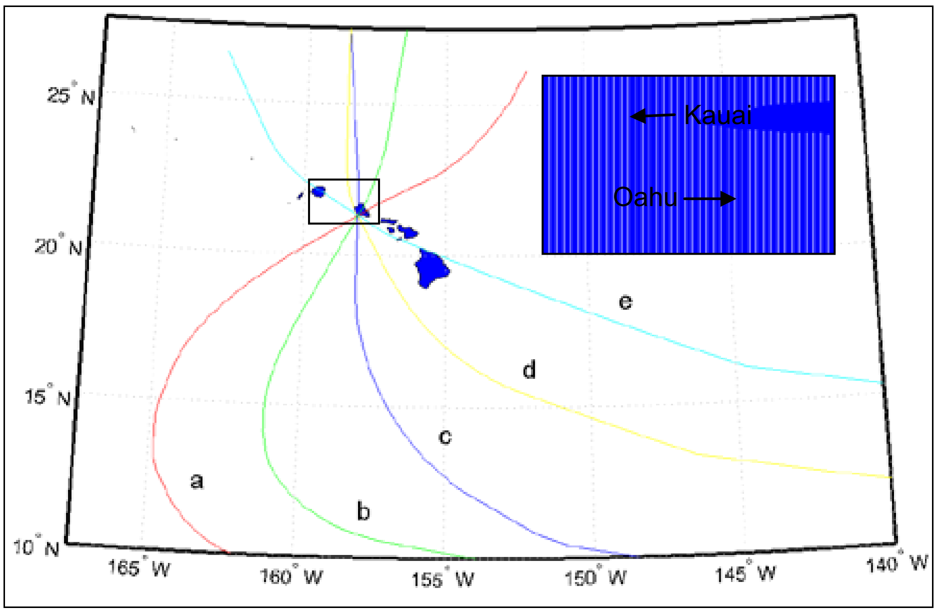

Figure 1. Hurricane storm tracks for database generation.

High-Fidelity Models. Waves and still water levels are computed with coupled circulation and wave models. The output from these models is then used to calculate wave runup on one-dimensional transects using a nonlinear Boussinesq model.

Coupled Circulation and Wave Models. The high-resolution models employed to create the fast forecast system are the ADvanced CIRCulation (ADCIRC) model (Luettich and Westerink 2004) and the unstructured version of the Simulating WAves Nearshore (SWAN) model (Booij et al. 1999, Ris et al. 1999, Zijlema 2010). ADCIRC and SWAN are tightly coupled and applied on the same unstructured mesh, allowing the models to run on the same computational cores and pass information efficiently through local memory (Dietrich et al. 2011). The unstructured mesh transitions from a coarse resolution offshore to a finer resolution to resolve nearshore bathymetry and waves and surge propagating into the surf zone and onto the floodplains.

ADCIRC solves a variant of the two-dimensional, depth-integrated (2DDI) shallow-water equations for water levels and the 2DDI momentum equations for currents (Kolar et al. 1994, Luettich and Westerink 2004, Dawson et al. 2006). ADCIRC was applied with a 1 sec timestep.

SWAN, a wave generation and transformation model, computes the evolution of wave action density using the action balance equation (Booij et al. 1999). The SWAN timestep and coupling interval are 600 sec. The wave directions were discretized into 36 bins of 10 deg constant width, and the frequencies were discretized on a logarithmic scale into 30 bins over the range of 0.031-0.55 Hz. This application uses the wind formulation based on Snyder et al. (1981), the modified whitecapping expressions of Rogers et al. (2003), the quadruplet nonlinear interactions via the Discrete Interaction Approximation of Hasselmann et al. (1985), and the bottom friction formulation of Madsen et al. (1988), where bottom roughness is calculated from a Manning n coefficient and the local water depth. Depth-induced breaking is computed with a spectral version of Battjes and Janssen (1978) with a breaking index $\gamma = 0.73$. Wave refraction was enabled where the resolution of the bathymetry was sufficient to prevent false refraction over one spatial element.

Coupled SWAN+ADCIRC were driven with wind and pressure fields generated by the planetary boundary layer model TC96 (Thompson and Cardone 1996). The inputs to TC96 were the hurricane track, landfall location, forward speed, central pressure, and radius of maximum winds. Simulations were run with a constant high tide of 0.4 m Mean Tide Level (MTL), and tidal variations in space and time were neglected.

Computational Mesh. The computational mesh employed in SWAN+ADCIRC covers a domain in the north central Pacific from the Equator to 35 deg North and 140 to 170 deg West. The mesh consists of 1,590,637 nodes and 3,527,785 elements. The mesh resolution varies from 30 m on land to 5000 m in deep water. The high-resolution areas include channels, coral reefs, and wave breaking zones. The computational domain and mesh resolution are shown in Figure 2.

Runup Model. Coupled SWAN+ADCIRC solves for wave heights and still water levels (i.e., storm surge) in the nearshore, but not for the time-varying runup at the shoreline. Wave runup can be on the order of several meters (vertical) above the still water level. In Hurricane Iniki, 6-8 m of runup was observed on Kauai (Cheung et al. 2003).

Runup was modeled across one-dimensional, cross-shore transects using the Boussinesq model BOUSS-1D (Demirbilek and Nwogu 2007). BOUSS-1D is a time-dependent, phase-resolving model. SWAN+ADCIRC water levels and waves applied along the offshore boundary of transects were transformed using BOUSS-1D to create a lookup table for the maximum runup and associated inundation for Kauai and Oahu.

Evaluation. After a matrix of storms covering the range of expected hurricane conditions was simulated using the high-fidelity models, these scenarios were used to create a surrogate model of the storm response. HAKOU is based on moving least squares response-surface approximations, and accesses the high-resolution model database as base points to estimate the maximum wave height and inundation (due to still water and runup) for any approaching or hypothetical storm. Figures 3 and 4 show the maximum wave height for a high-fidelity hurricane simulation and for HAKOU with the same input parameters, respectively. The overall agreement is quite good considering that the high-fidelity simulation requires a few thousand computation hours but HAKOU requires only a couple seconds.

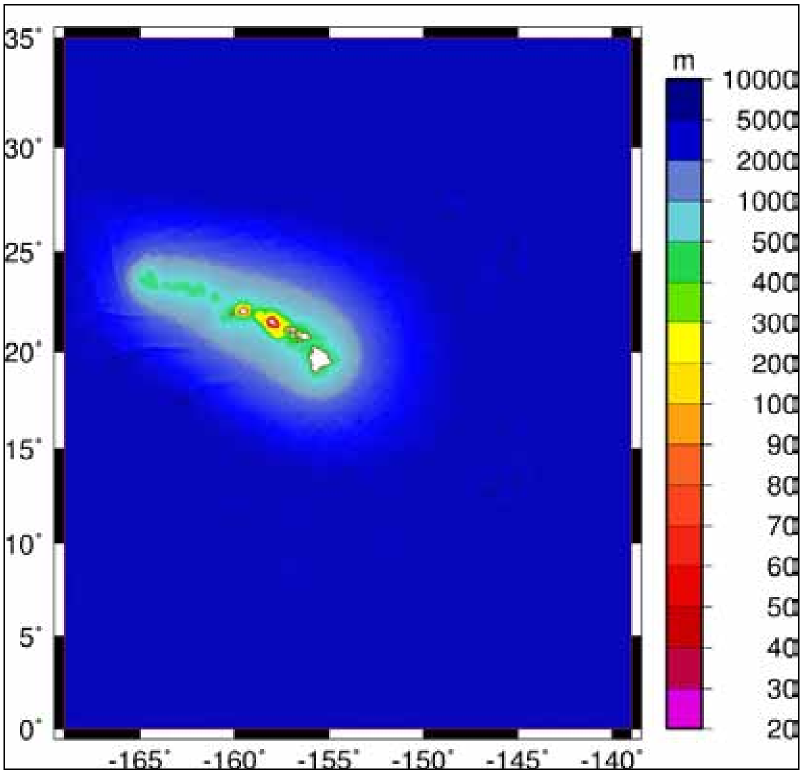

Figure 2. Computational mesh resolution of SWAN+ADCIRC.

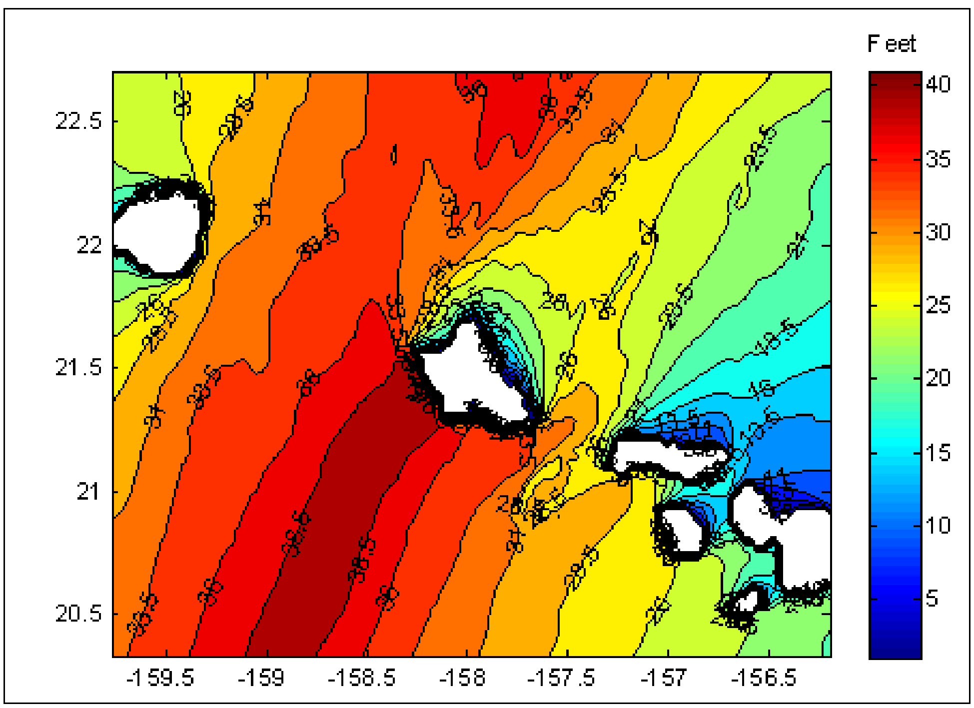

Figure 3. Maximum wave height for high-fidelity simulation.

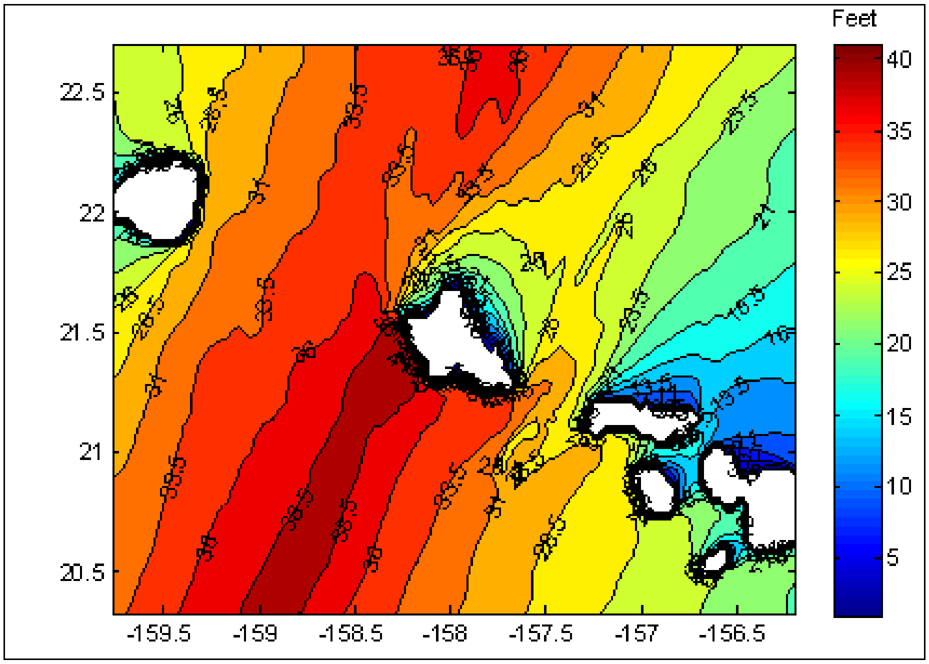

Figure 4. Maximum wave height for HAKOU.

Assessment Methods. HAKOU is able to produce deterministic and probabilistic hurricane predictions. Deterministic predictions evaluate a single known hurricane track in a couple seconds. However, there is a significant degree of uncertainty regarding hurricane characteristics and track (expressed as the cone of uncertainty by the National Hurricane Center (2010)) for a distant approaching hurricane. HAKOU can analyze the different responses resulting from these uncertainties and can present the hurricane risk as:

1. The average value over these scenarios,
2. The value that has a specific probability of being exceeded (e.g., values with a 10% chance of being exceeded), and
3. The probability the output will exceed a specific threshold (e.g., the probability the significant wave height will exceed 20 ft).

Probabilistic assessment of waves, surge, and inundation using HAKOU requires a few minutes of computational time, and can be quickly updated to accommodate updates to the forecast as the hurricane moves closer to landfall.

The capabilities of HAKOU v3 are assembled into an executable with a simple graphical user interface (GUI). The next section describes the outputs, installation, navigation, and execution of HAKOU v3.

HAKOU v3 SETUP AND EXECUTION:

Installation and Execution. HAKOU v3 requires the installation of the MATLAB Compiler Runtime (MCRInstaller.exe). The MCRInstaller.exe, distributed along with HAKOU, needs to be executed only once prior to running HAKOU for the first time. HAKOU is started using

HakouV3.exe, which can be placed in any folder on the computer. Shapefiles or KML files generated by HAKOU will be saved to this folder.

Graphical User Interface. The entire GUI for HAKOU is shown in Figure 5. The GUI has five panels:

1. The instruction and message panel,
2. The input panel,
3. The map panel,
4. The output selection panel, and
5. The figure generation panel.

Each of these panels is discussed in further detail below.

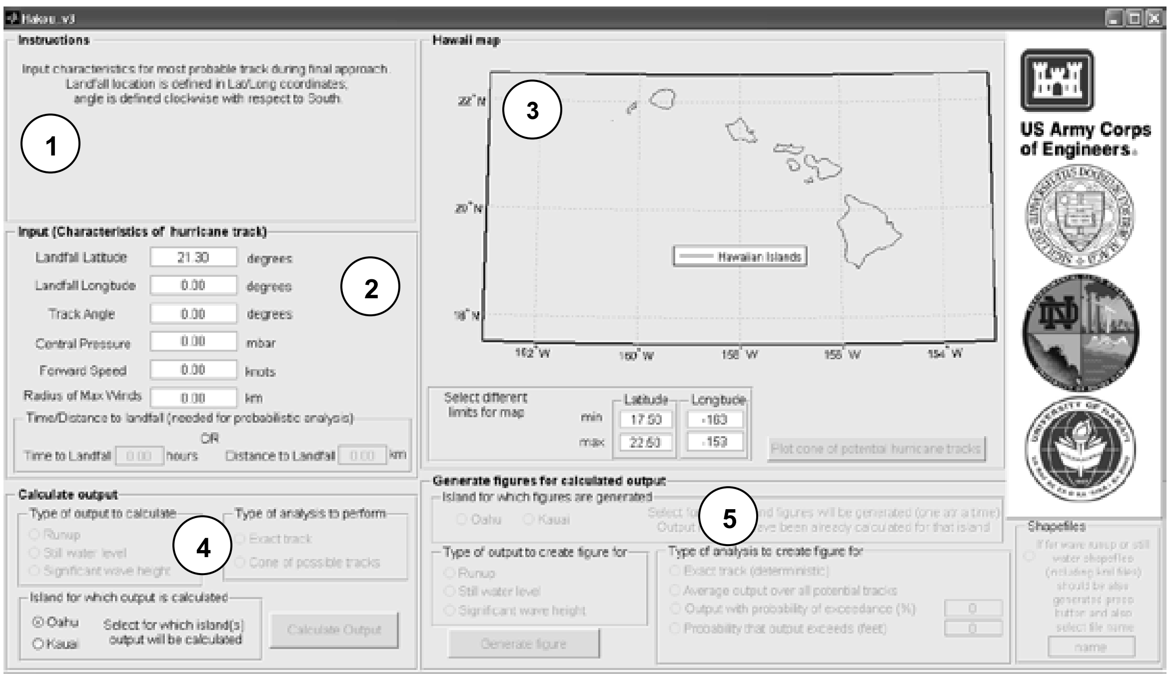

Figure 5. HAKOU v3 GUI.

Instruction and Message Panel. The instruction and message panel provides the user with various error messages and navigation directions for the GUI. This panel is updated throughout the execution of HAKOU.

Input Panel. The input panel defines the hurricane characteristics and track. The required inputs are:

1. Landfall location defined by latitude and longitude in deg. The latitude and longitude values must be between [20,22.5] and [-159.8,-157.5] deg, respectively. When a true landfall does not exist for the hurricane track (as when the hurricane passes between islands), then a virtual landfall is defined, e.g., where the hurricane crosses the 21.3 deg latitude line.
2. Track angle defined in deg and measured clockwise from North (α in Figure 6). The track angle must be between [110,260] deg.

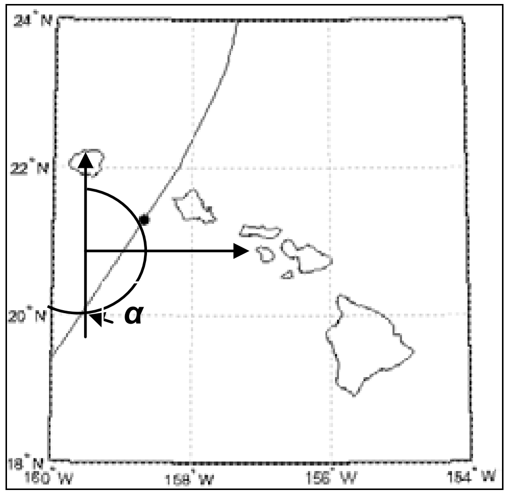

Figure 6. Track angle definition.

3. Central pressure in mbar. The central pressure must be between [930,980] mbar.
4. Forward speed in knots. The forward speed must be between [5,30] kts.
5. Radius of maximum winds in km. The radius must be between [15,60] km.

The “Time/Distance to landfall” subpanel is enabled once inputs (1-5) are defined. This subpanel determines the current location of the hurricane with respect to landfall. Input into either the “Time to Landfall” or “Distance to Landfall” field is required to perform a probabilistic assessment; only one field is required as they are related through forward speed and the other field will be automatically updated. The time before landfall has to be between [12,84] hours. Inputs into this subpanel activate the appropriate options throughout the rest of the GUI and allow the user to plot the cone of potential hurricane tracks on the map panel.

If inputs are not within the limits of the tool, an error message on the right of the input panel states the accepted range, and the input is automatically set to the minimum or maximum of the range, whichever is closest to the original input. An example of the input panel and an error message for the track angle is shown in Figure 7.

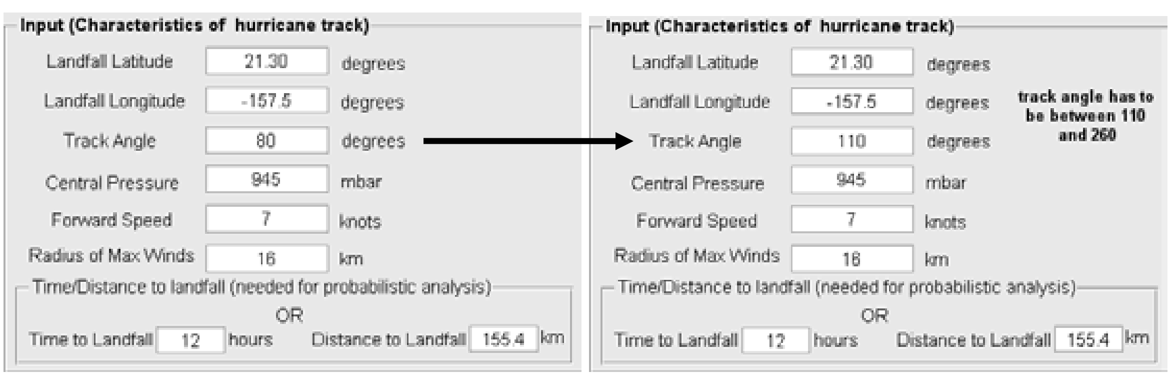

Figure 7a. Input panel. Figure 7b. Error message for track angle.

Map Panel. The map panel shows the islands of Hawaii, the landfall location, the hurricane track, and the cone of track uncertainty, if applicable. The map will automatically update to reflect a new track if inputs are changed in the input panel. The axes limits (zoom) of the viewing window may be changed using the lower left map subpanel. The latitude limits are [5,25] and the longitude limits are [-170,-130].

If input is provided to the "Time/Distance to landfall" input subpanel, the map panel then shows (Figure 8):

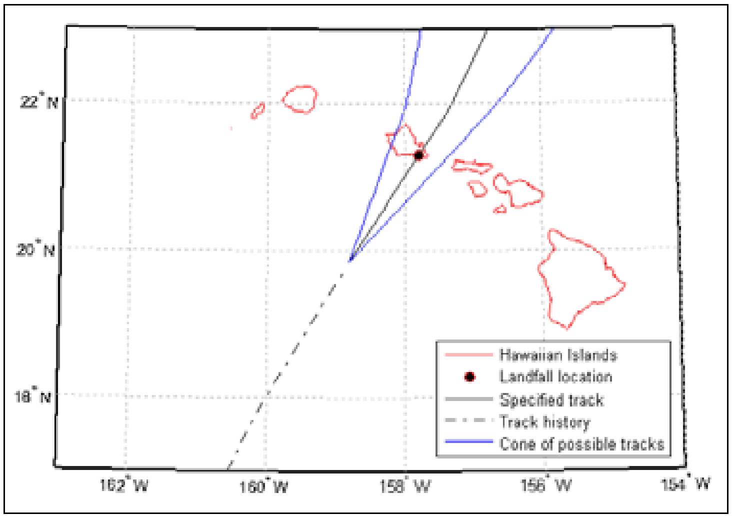

Figure 8. Hawaii map panel with time to landfall defined.

1. The hurricane track defined by the landfall location and track angle. The current location of the hurricane is defined based on the time to landfall and the forward speed. The track from the current location to landfall is shown with a solid line and the track history is shown with a dot-dash line.
2. The option to plot the cone of potential hurricane tracks. The cone is estimated based on National Weather Service standard prediction errors and has an 80 percent probability of containing the actual hurricane track. The width of the cone is influenced by the time until landfall (i.e., the uncertainty is greater for longer times and decreases as the storm nears impact). If the time to landfall is updated, the cone of potential hurricane tracks must be replotted.

Output Selection Panel. Once the hurricane track is defined in the input panel, all relevant buttons are enabled in the output selection panel. This panel is divided into three subpanels: (1) type of output to calculate; (2) type of analysis; and (3) which island is considered. HAKOU calculates three different outputs:

1. Maximum wave runup level (WRL) – defined as the vertical extent of maximum wave uprush of the individual wind waves over approximately a 1/2 hour period at maximum wave and water level conditions (accounts for breaking waves onshore),
2. Maximum still water level (SWL) – defined as the mean water level or storm surge (includes wind-driven surge, barometric surge, and wave setup),
3. Maximum significant wave height.

At least one type of output, one island, and one analysis must be selected. However, multiple selections may be simultaneously selected in all subpanels (e.g., deterministic and probabilistic analyses of runup, water levels, and wave heights can be done for both Oahu and Kauai at one time).

If the time or distance to landfall is undefined, only a deterministic or exact track analysis is allowed and the "cone of possible tracks" analysis is disabled. Otherwise, deterministic and probabilistic analyses can be completed. A deterministic analysis takes only a couple seconds while a probabilistic analysis will take a few minutes. Once at least one option is selected in each subpanel, the "Calculate Output" button becomes available and can be clicked to perform the selected calculations. A message in the instruction and message panel will alert the user to the beginning and completion of all calculations.

Figure Generation Panel. Once the calculations are completed, all relevant buttons in the figure generation panel are activated. The panel is divided into three subpanels that provide the following options for figure generation: (1) island selection, (2) output type, and (3) analysis type. Only one selection in each subpanel is allowed at a time. Figures can be created for the following analyses:

1. Deterministic evaluation – exact hurricane track;
2. Probabilistic evaluation – average over the cone of possible tracks;
3. Probabilistic evaluation – output that has a specific probability of exceedance. The probability in percent needs to be defined between [5,70] percent;
4. Probabilistic evaluation – probability the output will exceed a specified threshold. This option is only available for the wave height output and requires specification of the threshold between [5,50] ft.

After one option is selected in each subpanel, figures are generated using the "Generate Figure" button. Figures for different outputs or analyses must be generated one at a time. The figures are created in a separate window where a toolbar at the top offers a series of user controls, such the options to add a legend or save the figure in a selected format (**.jpg*, **.tiff*, **.fig*, **.bmp*, etc) (see Figure 9).

Figure 9. Toolbar.

Two figures of different resolution are created for the significant wave height output, as seen in Figure 10. One views a larger area around the islands while the other zooms in on the chosen island. The hurricane track on both figures appears as a solid line.

Additionally, the option to plot contours showing the probability of a wave height exceeding a specified threshold is available. Figure 11 shows an example plot of the probability of exceeding a 20 ft wave height.

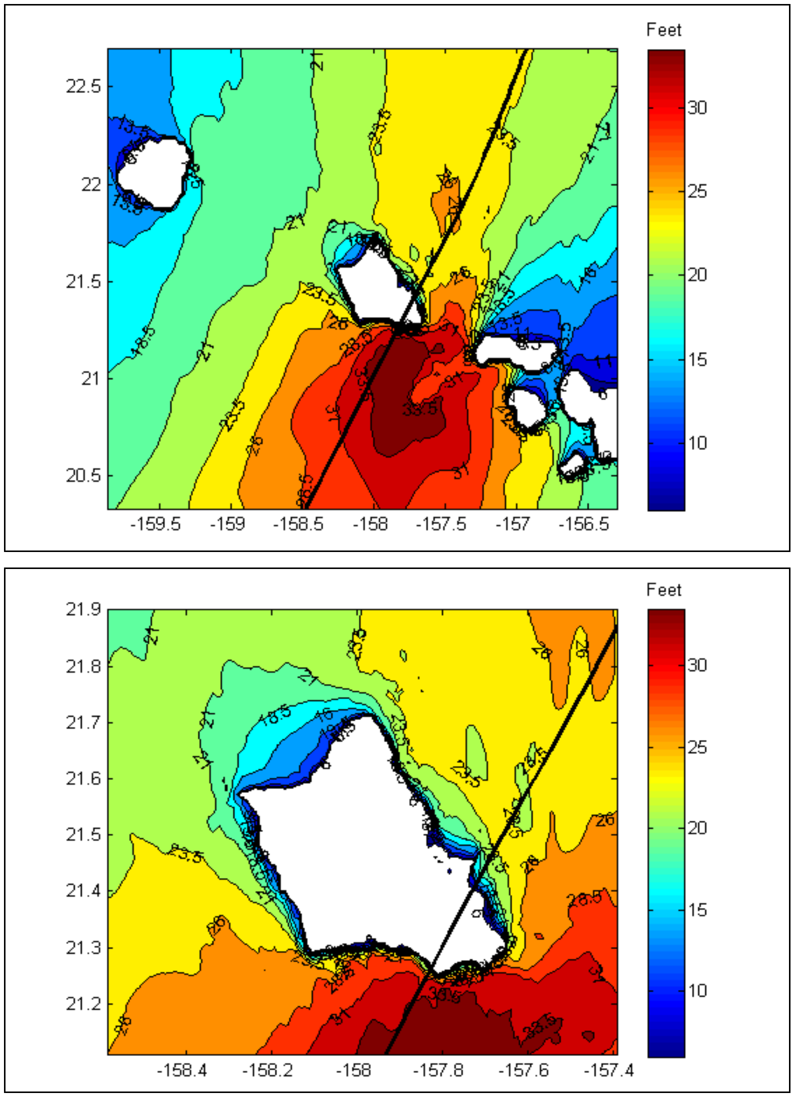

Figure 10. Figures generated for significant wave height; distant view (top) and zoomed to Oahu (bottom).

Shapefiles and KML files can be generated for the wave runup and still water level outputs using the shapefiles subpanel on the right. The name of the files can be modified in the lower text box. These files are saved in the same folder as the HAKOU executable and created with the generation of the figures. Still water level and runup contours for Oahu are shown in Figures 12 and 13, respectively. Figure 14 shows a runup KML file overlaid in Google Earth.

CONCLUSIONS: This CHETN describes HAKOU v3, a SWIMS fast forecasting tool for predicting hurricane inundation risk for the islands of Kauai and Oahu. Given five simple hurricane parameters, HAKOU forecasts maximum still water level, maximum wave runup level, and maximum significant wave height using response-surface modeling and support points from proven, high-resolution models. The fast forecasting system produces the storm response for deterministic assessment or probabilistic assessment based on the uncertainty cone of possible tracks and forecast error. While the high-fidelity models require thousand of computational hours, HAKOU provides deterministic predictions in seconds and probabilistic predictions in minutes.

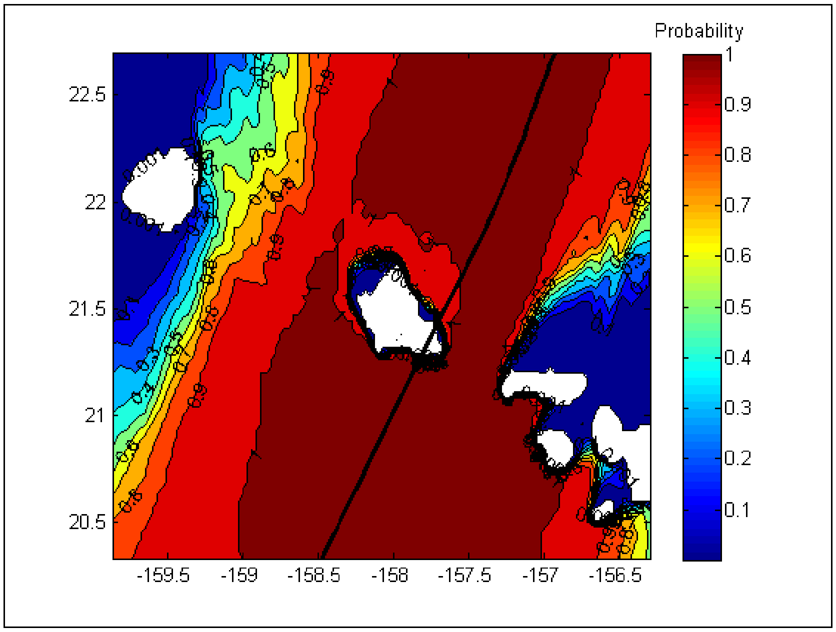

Figure 11. Probability wave height will exceed 20 ft.

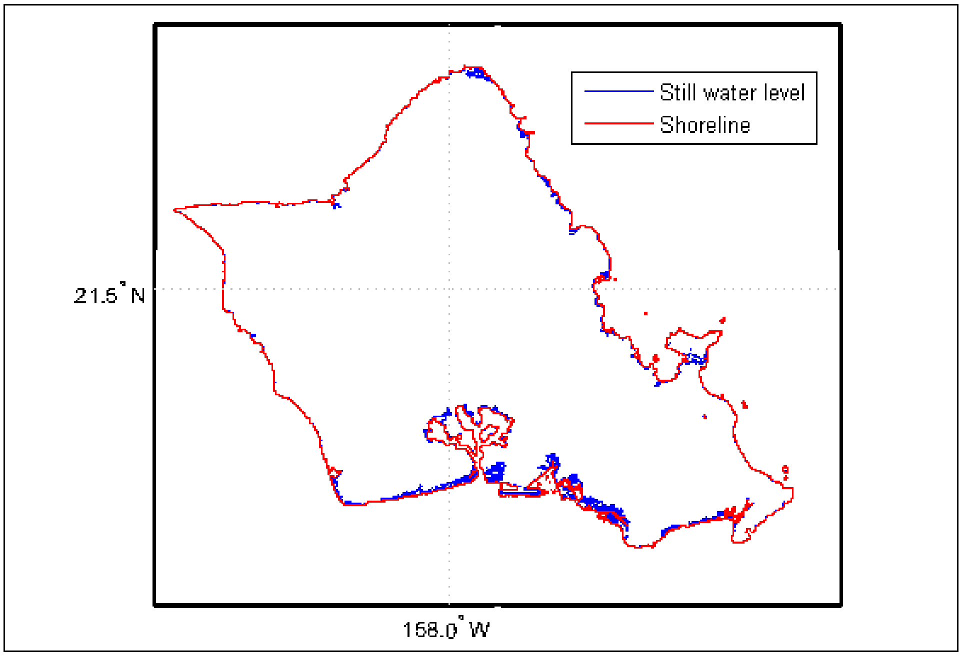

Figure 12. Still water level contours for Oahu.

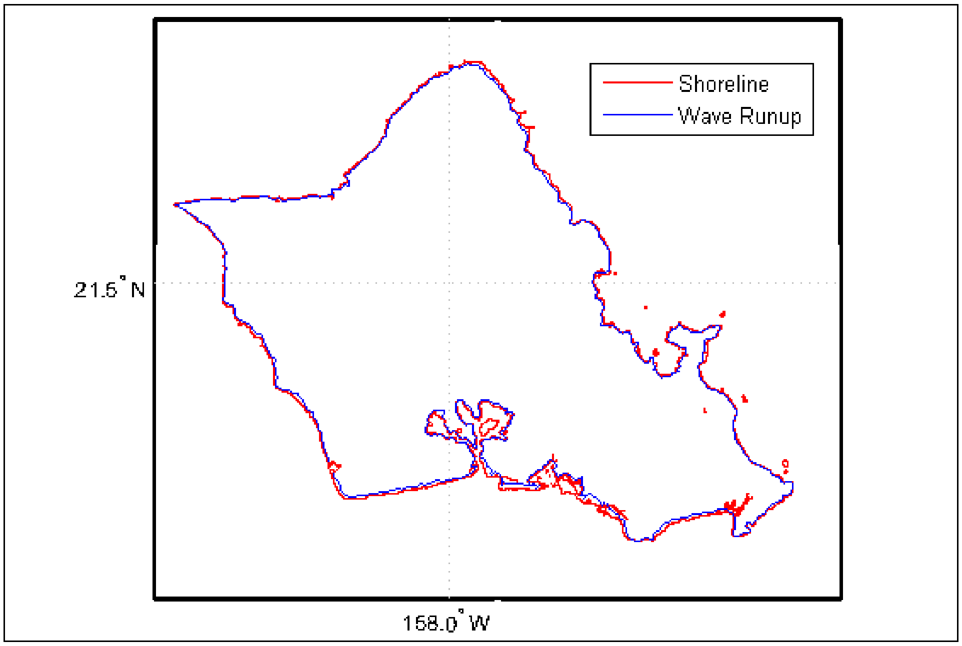

Figure 13. Wave runup contours for Oahu.

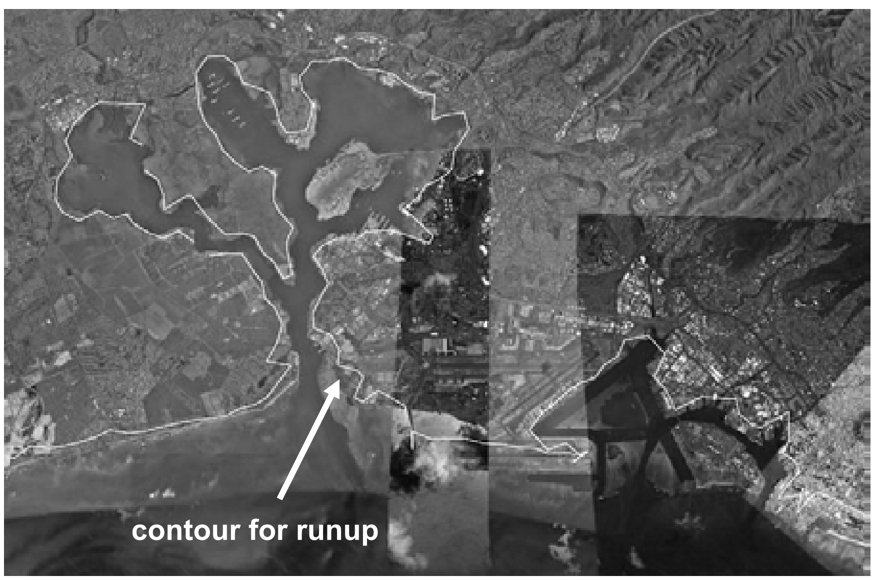

Figure 14. KML file uploaded in Google Earth. Runup contour indicated.

One of the benefits of HAKOU is the ability to quickly and interactively predict hurricane responses on Kauai and Oahu for hundreds of potential hurricanes using a simple GUI. These evaluations provide valuable information for engineering evaluation and emergency response. Coastal island storm response modeling includes tight coupling of complex processes, and further study and development of methodologies for analyzing storm hydrodynamics and their interaction with island coasts are needed. SWIMS is presently extending HAKOU to include the other populated Hawaiian islands.

AVAILABILITY: Contact Jane Smith (*Jane.M.Smith@usace.army.mil*) for information on acquiring HAKOU v3.

ADDITIONAL INFORMATION: This CHETN was prepared as part of the SWIMS project under the Coastal Field Data Collection Program and was written by Jane McKee Smith (*Jane.M.Smith@usace.army.mil*) and Mary E. Anderson (*Mary.Anderson@usace.army.mil*) of the U.S. Army Engineer Research and Development Center (ERDC), Coastal and Hydraulics Laboratory (CHL); Alexandros A. Taflanidis, Andrew B. Kennedy, and Joannes J. Westerink of the University of Notre Dame; and Kwok Fai Cheung of the University of Hawaii. The Program Manager is William Birkemeier, CHL. This CHETN should be cited as follows:

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